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STRUCTURAL METRICS TO ASSESS PROCESSES

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1 INTRODUCTION

As products are becoming more and more integrated and thus complex, so do design processes. In turn, process management puts more and more focus to continuously rework and improve design processes. Often, complex and confusing process maps or "wallpapers" are the result. Yet, there is little methodical support to systematically identify possible weak spots in such a process map.
The focus of this research is the identification of particular patterns in a process map and evaluating them through the systematic application of complexity metrics. These metrics are exclusively targeted on structural characteristics [1], i.e. patterns of how the different entities of the process are related to each other *qualitatively*. There are a number of other methodologies, e.g. CPM (critical path method), that evaluate processes quantitatively, for example with a focus to lead times or cost.
The metrics proposed here allow for easy examination of a given process map by pointing the user to features of the process that stand out. As such, the metrics do not necessarily indicate whether the occurrence of a certain feature is good or bad, but they only describe the process in a form that makes possible weak spots more easily accessible; a possible example might be spotting the one document that, if faulty, will induce errors into all subsequent tasks that use this one document.

2 EVALUATING PROCESSES: A SHORT STATE OF THE ART

Typically, processes are modeled as flow-oriented charts or process maps, which usually are graphically represented; common examples are e.g. SADT or IDEF. There are numerous tools on the market to support their modeling, e.g. ARIS or Innovator. Design Structure Matrices (DSM) [2] and Multi-Domain Matrices (MDM) [1], on the other hand, are an accepted means of modeling and analyzing the structural context of a system [3], either with view to a single native or aggregated domain (as with DSM) or to several concurrently prevailing domains (as with MDM). A single domain thus represents one specific "view" onto a process, e.g. the tasks or the organizational units. Entities of one domain can either be related among themselves, forming a DSM, or to entities of a different domain, using a Domain Mapping Matrix (DMM) [4]. The totality of all DSMs and DMMs forms a MDM that represents a multi-faceted network structure of a process. In fact, such a MDM is no longer flow-oriented, but it can contain further networks, e.g. the company organization or interfaces among IT-systems. Traditional flow-oriented models can be transferred into such MDMs without loss of information, and it is possible to recombine several different models in one MDM [5].
Complexity metrics have been researched for a long time, especially in information technology. Several authors have drawn attention to the fact that executing a software is much like running a workflow (being a more formalized process) [6, 7], stating that, therefore, software metrics are basically applicable to workflows. Besides basic metrics that count nodes, other metrics exist e.g. to evaluate the decision logics in workflows (e.g. the extension of McCabe's Cyclomatic Complexity [4]) or its behavior [8]. Also, e.g. the quality of the model of a workflow can be evaluated [9, 10].

3 METRICS TO EVALUATE THE STRUCTURE OF A PROCESS

In a collaborative project, possible metrics to evaluate an existing automotive design process were researched. Many of these metrics are based on structural characteristics as described in [1] that had to be converted to allow for numerical evaluation, and further metrics were derived from various publications focusing on software, workflow or process evaluation. In most cases, these metrics could be adapted to allow their use in design processes. As such, different groups of metrics were found that evaluate a process at a particular level of abstraction:

− Individual entities: comparison of individual entities of the process among each other
− Sub-structures of a complete system: analysis of how well entities can be regrouped according to various criteria
− Global structures: evaluation of the overall process in terms of size, coherence, and more
− Human cognition: representation of the degree, to which a user is able to understand the model
− Quality of the model: description of the coherence of the model regarding the meta-model
− Decision logics: determination of the impact of decision points on the structure of the process

Basically, all metrics are independent of the domain(s) they are applied to; while most metrics are applied to one domain at a time, there are also metrics that span several domains simultaneously. A metric only becomes reasonable and useful when applied to one (or several) specific domain(s), and only if it is appropriately interpreted.

E.g. the metric "weight of an edge" as shown in figure 1 can have different meanings. It counts all paths that follow each edge between any two nodes, thus assessing the relevance of an edge for a system. If all nodes in the figure were tasks, the metric would describe the importance of the relation between two tasks; if, for example, the task-task DSM would be sequenced (i.e. put into an optimum order), the metric could point to relations that are of lesser importance and that can possibly reordered. If the nodes were personnel, the metric could e.g. point to important channels of reporting. Each time, the distribution of the metric for all edges can then be used to compare all edges among themselves.

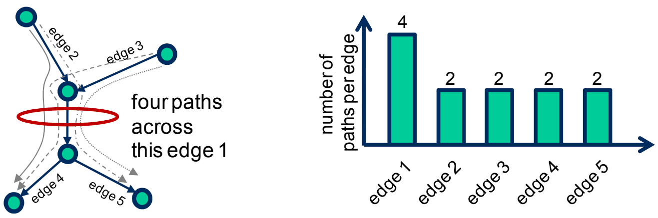

Figure 1. Metric for the weight of an edge

4 REFLEXION

The metrics that are presented here are meant to complement existing approaches for process analysis. While common, existing approaches of process analysis rather focus on quantitative models, structural metrics put the regard on qualitative models, i.e. a representation of the structure of a process. To this end, different possible structural characteristics are evaluated numerically.

An extensive case study was undertaken to scrutinize a large automotive design process consisting of several thousand entities (activities, documents, milestones) organized within 15 sub processes. Individual results that would point to one or more interesting entities (e.g. important documents, central tasks that coordinate a process or critical milestones) could be identified within all domains and for all metrics that were applied. In fact, the metrics turned out to be a appropriate to evaluate the large process map that otherwise would have needed much more work to analyze.

The structural metrics presented thus allowed to draw a comprehensive picture of a process. All metrics that were designed are based on existing metrics taken from comparable environments (software programs or workflow design), or they are based on structural characteristics that, so far, have not been evaluated numerically but that are based on previous application in similar systems. In doing so, it was possible to base all metrics on existing empirical evidence as to the validity of their application and on experience about the extent, to which interpretations are possible.

The high degree of abstraction necessitates the critical reflection of the application, implementation and interpretation each time the metrics are used. The necessary framework to systematize possible results that can be drawn from the use of structural metrics is still under work. However, as the application in the case study has shown, the metrics allow for the individual analysis of a process as well as for a follow-up of its evolution over time, e.g. to schedule the maintenance of a workflow.

At the same time, the high degree of abstraction allows to analyze processes top down and compare results across several processes to strategically guide process improvement activities. Although this bears, of course, the tendency to compare what cannot be compared, it enables management to base decisions on more than a gut feeling. In fact, the metrics can provide a tool similar to a Balanced Scorecard for process improvement activities.

The analysis must be based on complete modeling of a process. Only if sound data is used, the results can be trusted fully. Yet, process models in industry are rarely complete, mostly because it is either too time-consuming to obtain a complete model or because the procedures that are modeled often cannot be turned into one coherent model simply because there is no unique single way that things are done. For such incomplete data, the approach has proven possible, too, as even for sub-sets of a process relevant results can be found. If, e.g. only a part of a process model is complete, at least the entities within this part of the network will shop up in the analysis.

Furthermore, the models that the analysis is based on must be coherent. In fact, each individual basic metric is, at first, independent of a specific domain and type of relationship, and thus void of a deeper meaning. However, when selecting a domain (e.g. tasks) and relationship type (e.g. task A generates a document that starts task B), it is possible to interpret the results a metric shows in a particular way. If, for example, the relative centrality of all task is evaluated, a few tasks will show up, around which all documents in the process revolve.

A coherent design of a process model is mostly ensured by the underlying modeling scheme or meta-model; in Germany, this would mostly be the ARIS House of Business Engineering (HOBE). Many others are available, too. For the case study, the data was taken from several independent models and combined into one MDM. However, the common approach is mostly to not construct the MDM directly but to parse the data from existing models that prescribe a certain semantics. With the possible regard to analyze these models using structural metrics, however, the stringent use of that semantics is all the more important.

Unfortunately, no absolute judgment whether a process is “good” or “bad” can be derived from the application of the metrics; however, tendencies are possible, although even this is subject to how each company wants to develop or how things are done in that company.

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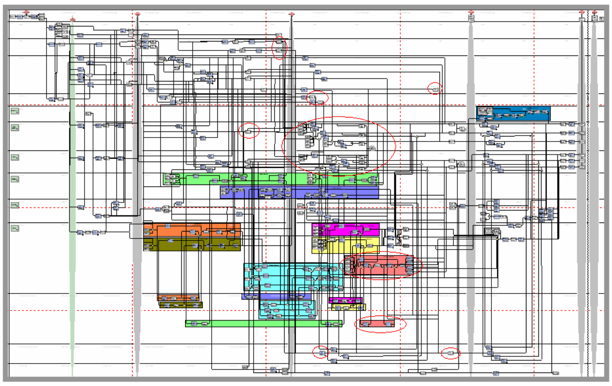
Introduction

- Process management is an important asset in industry
  - Processes become more and more complex
  - Process improvement is largely based on experience
- Process improvement necessitates
  - Systematic analysis of existing processes
  - Detection of possible weak spots
  - Evaluation of each weak spot to know whether it needs improvement
- Process complexity consists of
  - Structure
  - Arrangements
  - Interaction
  - Inference
  - Response
  - Understandability



Exemplary design process from automotive industry

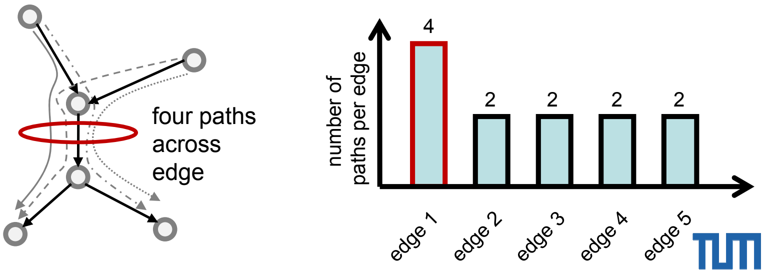
Cardoso, J.: Approaches to Compute Workflow Complexity. Dagstuhl Seminar „The Role of Business Processes in Service Oriented Architectures", 16 – 21 July 2006, Dagstuhl, Germany

FOLLOW THE FLOW OF INFORMATION!
MANAGE COMPLEX SYSTEMS

Problem Description

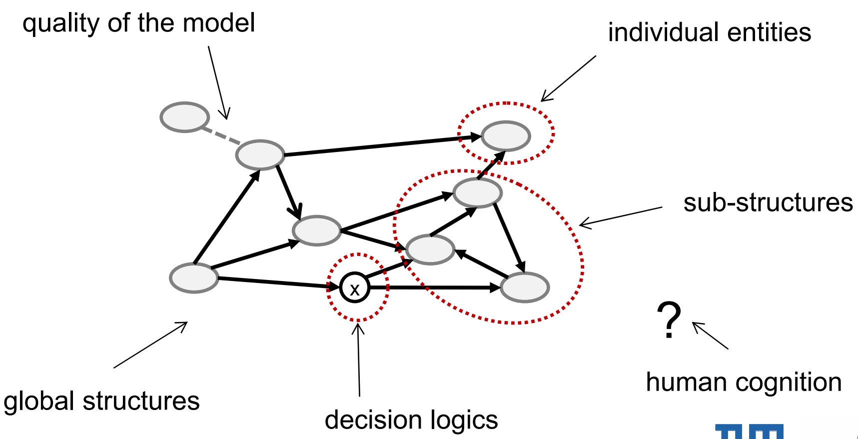
Development of **structural process metrics**

- Work with qualitative models
- Work with (in)complete data sets
- Represent more than just the flow of information
  - All necessary domains (tasks, documents, milestones,…)
  - Interdependencies within and among domains: process as multi-layered network
- Systematic analysis of process
  - Methodical support to evaluate structural characteristics
  - Flexibility of metrics to apply to different domain
  - Comprehensive picture of process

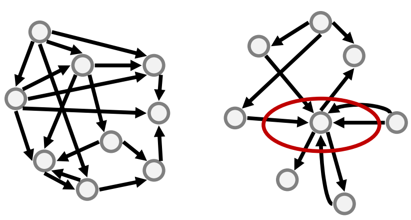


Different Kinds of Metrics to evaluate the Structure of a Process

- Represent a complete picture of a process
  - Different layers of detail – look into the global and the details
  - All kinds of entities – allow for analysis of all common process models
  - High level of abstraction – compare processes
  - Different views – involve possible stakeholders

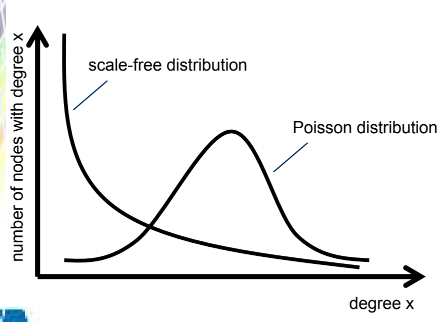


Example of a Metric – Activity / Passivity (single node)



Poisson distribution (random)

scale-free distribution (hub and spoke)



Definition

- Sum of incident and outgoing edges (= incident / outgoing degree of node)

Possible meaning

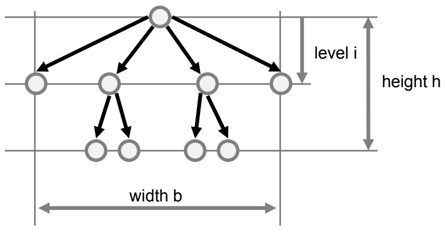
- Homogeneity of network
- Sensitivity of network to the malfunction or drop-out of individual nodes
- Identification of critical nodes that can cause a failure of the overall network

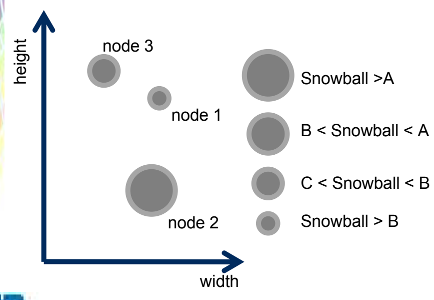
Representation of metric

- Plot of distribution of degree for incident and for outgoing edges

Albert, R., Barabási, A.: Statistical mechanics of complex networks. Rev. of modern Physics (2002) 74, S. 47-97)

Example of a Metric – Snowball factor (single entity)





Definition

- Surface (height and width) of a hierarchy, weighted according to levels
- Alternatively: height and with of a hierarchy

Possible meaning

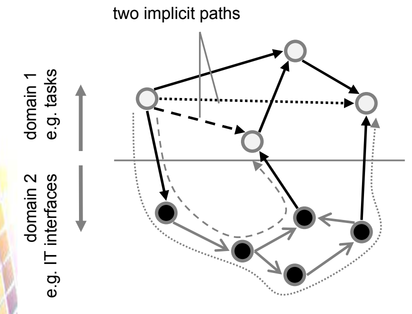
- Distribution of information and errors within the network
  - Analysis for nodes that are robust against the propagation of errors
  - Analysis of nodes that are central distributors of information
- Calculation is possible for consequences (= active root node of hierarchy) or forerun (= passive root node of hierarchy)

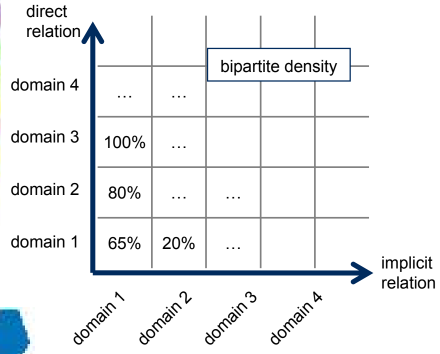
Representation of metric

- Metric for each node that is a root node
- Portofolio of width, height and snowball-factor (ABC analysis)

Loch, C., Mihm, J., Huchzermeier, A., Concurrent Engineering and Design Oscillations in Complex Engineering Projects, CERA Concurrent Engineering: Research and Applications, Volume 11, Number 3, September 2003.

Example of a Metric – Bipartite density (one or more domains)





Definition

- Percentage of implicit relations (within the same or via a different domain) and number of direct relations

Possible meaning

- Comparison of alignment with other domains
  - Team structures and process
  - IT-interfaces and flow of documents
  - …
- Analysis of appropiateness of direct relations

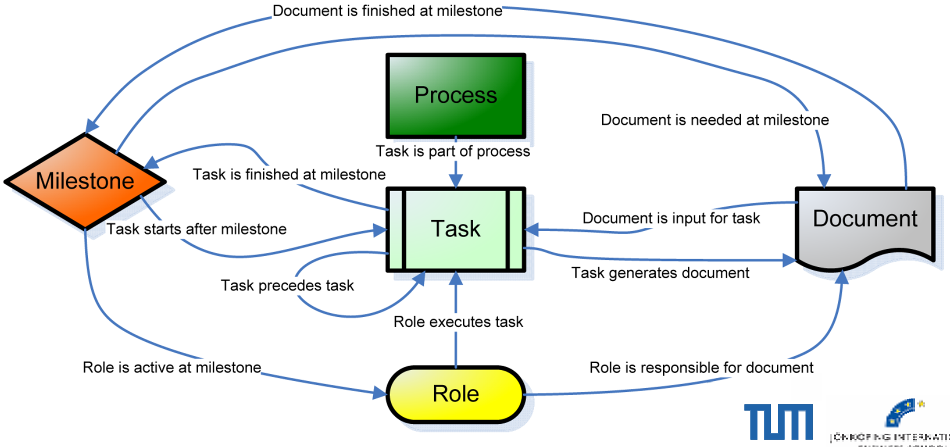
Representation of metric

- metric for each domain related to another domain

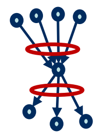
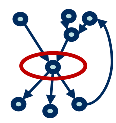
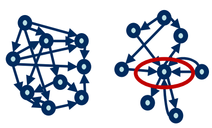
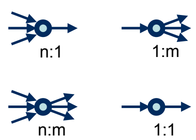
Vanderfeesten, I., Cardoso, J., Mendling, J., Reijers, H. A., van der Aalst, W., Quality Metrics for Business Process Models, 2007 BPM and Workflow Handbook, Fischer, L. (ed), Future Strategies, Lighthouse Point 2007

Domain-specific Evaluation of Structural Characteristics

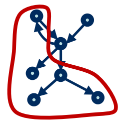
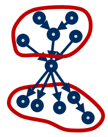
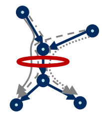
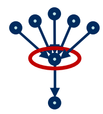
- Each metric is – at first – independent of a domain
  - Selection of domain(s) necessary
  - Interpretation of metric depends on
    - Type of domain(s)
    - Type of relationship
- Process metamodel for this process analysis



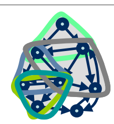
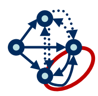
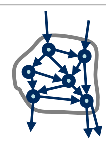
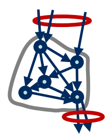
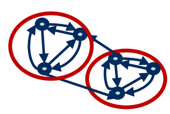
Possible Metrics – An Overview

activity / passivity	number of outgoing edges (activity) or incident edges (passivity)	• intensity of changes that a node exerts or receives on its immediate neighbors • quick estimation of nodes that are highly relevant or critical for the network	
relative centrality based on between-ness	sum of active and passive closeness divided by reachability of node	• degree of communication activity in the network • degree of integration into the network • potential of a node to influence the network • identification of hubs in the network	
degree distribution	number of nodes with identical activity or passivity	• homogeneity of network • sensitivity of network to the malfunction or drop-out of individual nodes • identification of critical nodes that can cause a failure of the overall network	
degree correlation	correlation of individual values of degree distribution	• degree, to which a node impacts (or is impacted by) the network • tendency, to which the network relies on individual nodes to coordinate the overall structure	

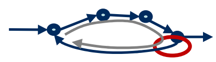
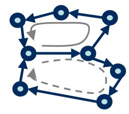
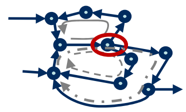
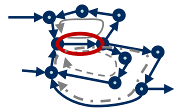
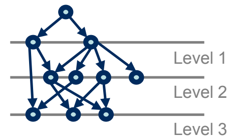
Possible Metrics – An Overview

number of reachable nodes	number of nodes to be reached from starting node (number of leaves for each root node of a tree)	• degree of Influence of a node onto the overall network • influence is not weighted according to distance (cf. hierarchy)	
reachability of a node	number of starting nodes to reach node, divided by total number of nodes	• influence of the overall network onto a node • influence is not weighted according to distance (cf. hierarchy)	
closeness	total length of all paths that cross a node	• compactness of a network from a node's point of view • estimation of velocity of reaching other nodes in the network • degree of immediacy of influence on / by other nodes	
weight of an edge	number of paths that follow an edge	• importance of an edge for the overall network • identification of critical edges	
synchro-points / distributors	number of AND-joins or -splits (merging / distributing busses)	• identification of critical coordination points • also possible for OR-joins	

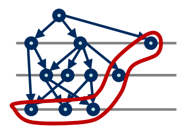
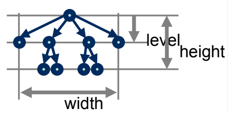
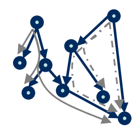
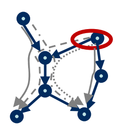
Possible Metrics – An Overview

cluster-coefficient (global)	sum of all local cluster-coefficients divided by total number of nodes	• evaluation of tendency of individual nodes to be part of a cluster • comparison of clustering of different networks	
cluster-coefficient (local)	quotient of number of existing edges between nodes adjacent to a node and number of possible edges	• evaluation of tendency of individual nodes to be part of a cluster • identification of nodes that are not fully involved in cluster • identification of potential synchronisation / distribution nodes	
module quality	product of number of edges that cross the border of the module and number of edges within module	• degree of closeness of a module • only sensible to evaluate existing clusters • comparison of modules concerning their interaction with their environment	
fan criticality	activity / passivity for a module (number of outgoing or incident edges for a group of nodes)	• similar to activity / passivity • only sensible for the evaluation of existing modules • comparison of modules concerning their susceptability to changes	
number of cliques	number of complete clusters	• identification of closely connected groups that involve a lot of communication	

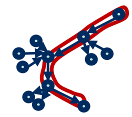
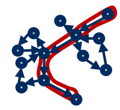
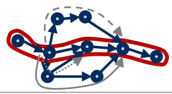
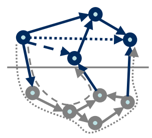
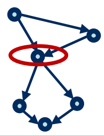
Possible Metrics – An Overview

iteration - starting points	number of nodes that start a cycle (lowest node in triangularized DSM)	• criticality of a node to start an iteration • determination of possible decision points that can cause iterations	
number of cycles	number of paths with identical starting- and end-node	• evaluation of the overall uncertainty of the process	
number of nodes in cycles	occurrence of a node in all cycles	• determination of core nodes that help cope with uncertainty in the process • determination of nodes that have an important • impact on the quality of the result of the overall process	
number of edges in cycles	occurrence of an edge in all cycles	• communication channels that are highly relevant to coping with uncertainty in the process	
height of hierarchy	number of levels of a tree	• evaluation of intensity of distribution of information or errors • possible as impact on other nodes (active root node) or as feed (passive root node) • evaluation of secondary effects of changes to a node	

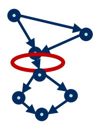
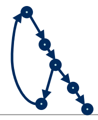
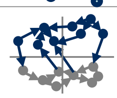
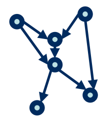
Possible Metrics – An Overview

width of hierarchy	number of leafs per level of a tree	• evaluation of velocity of distribution of information or errors per level • possible as impact on other nodes (active root node) or as feed (passive root node) • evaluation of secondary effects of changes to a node	
tree criticality	surface of a tree (width, height), weighted according to level (active root node = snowball factor, passive root node = forerun-factor)	• distribution of information and errors within the network • analysis for nodes that are robust against the propagation of errors • analysis of nodes that are central distributors of information • calculation is possible for consequences (= active root node of hierarchy) or forerun (= passive root node of hierarchy)	
tree-robustness	quotient of number of all trees and sum of all tree criticalities	• degree to which the network is interspersed with trees • evaluation of robustness against rapid propagation of errors	
number of paths	number of all possible paths per set of start- / end-nodes	• evaluation of redundant pathways through the network • determination of clarity of processing of process • determination of critical start- and end-nodes	

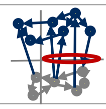
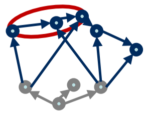
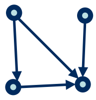
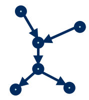
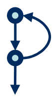
Possible Metrics – An Overview

centrality of path	sum of all activities or passivities of all nodes along path OR sum of all centralities of all nodes along path	• evaluation of relevance of an individual path for the overall process • identification of critical transitions and pathways through the process	
iterative oscillation	sum of length of all cycles that share at least one edge with a path	• degree, to which a path interacts with other nodes based on uncertainty within the process • determination of pathways through the network that are highly impacted by uncertainty	
progressive oscillation	sum of length of all paths that run in parallel to path	• evaluation of the impact of supporting processes for an individual pathway • determination of the dependency on supporting processes	
bipartite coupling	percentage of implicit relations (within the same or via a different domain) and number of direct relations	• comparison of alignment with other domains (Team structures and process, IT-interfaces and flow of documents, … • Analysis of appropriateness of direct relations	
node connectivity	number of nodes that need to be removed to separate the network into two/three/… disjoint networks	• evaluation of the robustness of the network against single nodes dropping out • tendency of the network to keep its overall structure in case a node fails • identification of nodes that are critical to the overall network	

Possible Metrics – An Overview

edge connectivity	number of edges to be removed to separate the network into two/three/… disjoint networks	• evaluation of the robustness of the network against single edges dropping out • tendency of the network to keep its overall structure in case an edge fails • identification of edges that are critical to the overall network	
number of returns	number of elements that impede a complete triangularization of a DSM	• evaluation of the degree of uncertainty in the process • determination of the degree of deviation from an ideal sequence	
number of domains	number of domains	• evaluation of the multi-facetedness of the network • number of possible views onto and stakeholders in a network	
number of nodes	number of nodes per domain	• size of the network • assessment basis to out other metrics into perspective	
number of different nodes	number of nodes that do not bear the same name	• evaluation of the diversity of the network • relativization of node count when using object-oriented models (i.e. when nodes are instantiated several times)	
edges per node	quotient of number of edges and number of nodes	• evaluation of the density of the network	

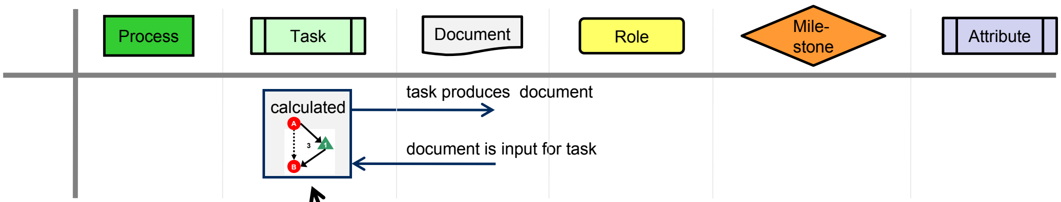
Possible Metrics – An Overview

interfaces (domains)	number of edges between two domains	• determination of the importance of a domain for the overall network • evaluation of the size of the interface between two domains	
interfaces (orga-nization)	number of edges within one domain that link two nodes, which are not attributed to the same node in a different domain	• analysis of the effort taken for a transition between two nodes because the node of reference is changed (e.g. different responsibility, different format, different media, different model,…) • identification of transitions that demand special interfaces • comparable to swimlane-model	
relational density	quotient of number of edges in a domain and number of possible edges	• evaluation of the density and intensity of the network	
cognitive volume	number of dimensions to obtain a planar graph	• evaluation of the network's understandability • determination of the ascertainability of the network model • description of the transparency of the process model	
cognitive weight	based on empirically founded characteristic values	• description of the human ability to grasp individual parts of the network as well as its global structure	

Applying the Metrics to a Process

Automotive Design Process (design of control devices)

- Overall MDM assembled from different sources within company
  1860 nodes in seven domains, 7070 native dependencies
- Calculation of DSMs out of various dependencies
  e.g. „task initates task“ via documents that are generated on the way
- Mixed quality of data – evaluation of all possible metrics
  - Each metric attributed to domains where useful
  - Navigator for domains to indicate nature (native, calculated) and type of domain
  - Interpretation individual to each metric

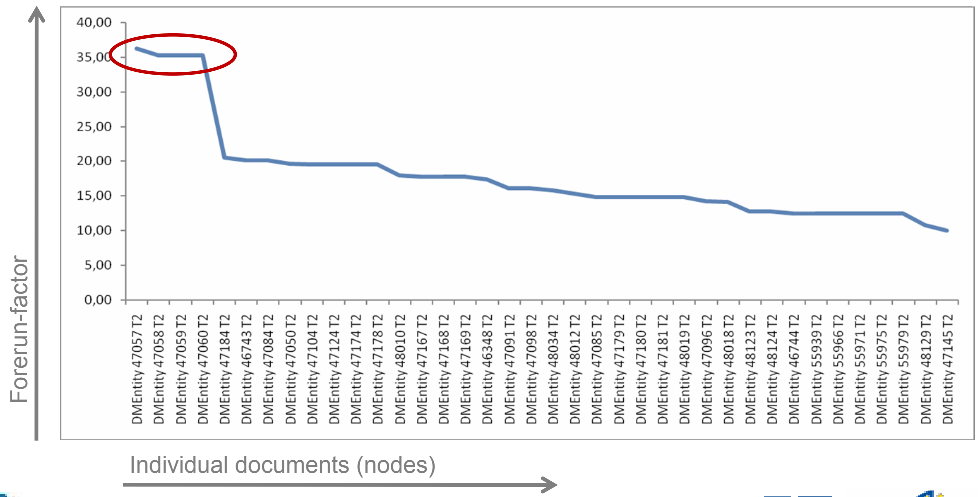


Example for a calculated DSM
to be evaluated by metric
„forerun-factor“

Case Study

Forerun-factor: Document-Document-DSM (via tasks)

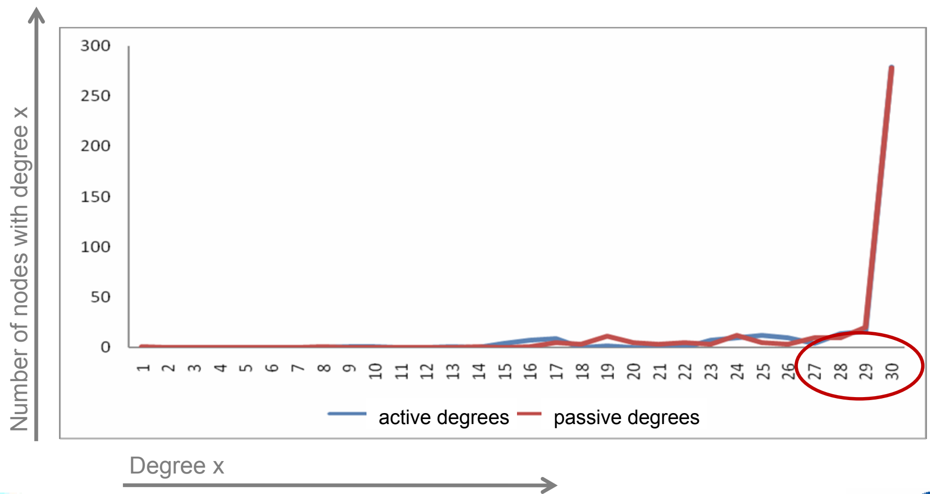
- evaluation of passive hierarchies onto nodes
- 4 core documents (ABC analysis) that receive changes across overall process
- equal impact of documents on most other documents in process



Case Study

Degree distribution: task-task-DSM (via documents)

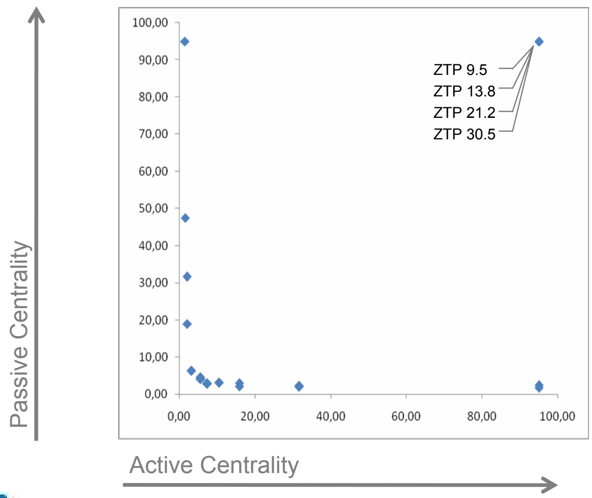
- process is scale-free (hub-and spoke)
- some core nodes coordinate the overall network
- Core nodes can make the overall process fail easily



Case Study

Relative Centrality: milestone-milestone-DSM (via tasks)

- 4 core milestones control overall process
- most milestones have little impact on other milestones



Conclusion

- Process metrics
  - Many metrics are possible
    - Empirical foundation necessary
    - Relevance for domains is case-dependent
  - Applicability
    - Quick evaluation of large process networks
    - Identification of possible „weak spots“
  - Combination of metrics
    - Several metrics necessary to fully characterize a process network
    - Possible „structural balanced scorecard“
- Further work
  - Framework to select metrics
    - Dependent on goals of process analysis
    - Mutually dependent or orthogonal metrics
    - Application to different domains (complete meta- or reference-model)
  - Development of algorithms
  - Evaluation using different examples of processes